Lecture 13: Colors of stars

Astronomy 111
Colors of Stars

- Stars are made of hot, dense gas
  - *Continuous* spectrum from the lowest visible layers (“photosphere”).
  - Approximates a *blackbody* spectrum.
- From Wien’s Law, we expect:
  - hotter stars appear **BLUE** (T=10,000-50,000 K)
  - middle stars appear **YELLOW** (T~6000K)
  - cool stars appear **RED** (T~3000K)
Spectra of Stars

- Hot, dense lower photosphere of a star is surrounded by thinner (but still fairly hot) atmosphere.
  - Produces an *Absorption Line* spectrum.
  - Lines come from the elements in the stellar atmosphere.
Spectral Classification of Stars

• Astronomers noticed that stellar spectra showed many similarities.
• Can stars be classified by their spectra?
• Draper Survey at Harvard (1886-1897):
  – Objective Prism Photography
  – obtained spectra of >100,000 stars
  – hired women as “computers” to analyze spectra
Harvard "Computers" (c. 1900)
Objective Prism Spectra
Harvard Classification

Edward Pickering’s first attempt at a systematic spectral classification:
- Sort by Hydrogen absorption-line strength
- Spectral Type “A” = strongest Hydrogen lines
  - followed by types B, C, D, etc. (weaker)

Problem:
Other lines followed no discernible patterns.
Annie Jump Cannon

• Leader of Pickering’s “computers”, she noticed subtle patterns among metal lines.
• Re-arranged Pickering’s ABC spectral types, throwing out most as redundant.
• Left 7 primary and 3 secondary classes:
  • O  B  A  F  G  K  M  (R  N  S)
• Unifying factor: *Temperature*
Annie Jump Cannon
The Spectral Sequence

Spectral Sequence is a *Temperature* Sequence

O  B  A  F  G  K  M  L  T

Hotter → 50,000K  ← Bluer

Cooler → 2000K  → Redder
Spectral Types

Hydrogen Balmer series: H lines

O
B
A
F
G
K
M

350 nm 400 nm 450 nm 500 nm

K H Ionized Ca Calcium Various metals
Stellar spectra in order from the hottest (top) to coolest (bottom).
The Spectral Sequence is a Temperature Sequence

- Gross differences among the spectral types are due to differences in Temperature.
- Composition differences are minor at best.
  - Demonstrated by Cecilia Payne-Gaposchkin in 1920’s
- Why?
  What lines you see depends on the state of excitation and ionization of the gas.
Example: Hydrogen Lines

- Visible Hydrogen absorption lines come from the second excited state.
- **B Stars (15-30,000 K):**
  Most of H is ionized, so only very weak H lines.
- **A Stars (10,000 K):**
  Ideal excitation conditions, strongest H lines.
- **G Stars (6000 K):**
  Too cool, little excited H, so only weak H lines.
O Stars

- Hottest Stars: $T > 30,000$ K
- Strong lines of He$^+$
- No lines of H
B Stars

- $T=15,000 - 30,000 \text{ K}$
- Strong lines of He
- Very weak lines of H
A Stars

- \( T = 10,000 \text{ – } 7500 \text{ K} \)
- Strong lines of H
- Weak lines of Ca+
F Stars

• $T = 7500 - 6000 \text{ K}$
• weaker lines of H
• $\text{Ca}^+ \text{ lines growing stronger}$
• first weak metal lines appear
G Stars

- $T = 6000 - 5000$ K
- Strong lines of $\text{Ca}^+, \text{Fe}^+, \&$ other metals
- much weaker H lines

- The Sun is a G-type Star
K Stars

- Cool Stars: $T = 5000 \text{ – } 3500 \text{ K}$
- Strongest metal lines
- H lines practically gone
- first weak CH & CN molecular bands
M Stars

- Very cool stars: $T = 2000-3500$ K
- Strong molecular bands (especially TiO)
- No lines of H
L & T Stars

- Coolest stars: \( T < 2000 \) K
- Discovered in 1999
- Strong molecular bands
  - Metal-hydride (CrH & FeH)
  - Methane (CH4) in T stars
- Probably not stars at all
An understanding of atomic physics and better techniques permit finer distinctions.

Morgan-Keenan (M-K) Classification System:

Start with Harvard classes:

• O  B  A  F  G  K  M  L  T

Subdivide each class into numbered subclasses:

• A0  A1  A2  A3  ...  A9
Examples

• The Sun:
  G2 star

• Other Bright Stars:
  Betelgeuse: M2 star (Orion)
  Rigel: B8 star (Orion)
  Sirius: A1 star (Canis Major)
  Aldebaran: K5 star (Taurus)
Summary of Stellar Properties

- Large range of Stellar Luminosities:
  - $10^{-4}$ to $10^6 \, L_{\text{sun}}$
- Large range of Stellar Radii:
  - $10^{-2}$ to $10^3 \, R_{\text{sun}}$
- Modest range of Stellar Temperatures:
  - 3000 to >50,000 K
- Wide Range of Stellar Masses:
  - 0.1 to ~50 $M_{\text{sun}}$
Luminosity-Radius-Temperature Relation

• Stars are approximately black bodies.

Stefan-Boltzmann Law:  
energy/sec/area = \( \sigma T^4 \)

The area of a spherical star:  
area = \( 4\pi R^2 \)

• Predicted Stellar Luminosity (energy/sec):  
\[ L = 4\pi R^2 \sigma T^4 \]
Example 1:

- 2 stars are the same size, \( R_A = R_B \), but star A is 2× hotter than star B \( (T_A = 2T_B) \):

\[
\frac{L_A}{L_B} = \frac{4\pi R_A^2 \sigma T_A^4}{4\pi R_B^2 \sigma T_B^4} \quad \Rightarrow \quad \frac{L_A}{L_B} = \left(\frac{2T_B}{T_b}\right)^4
\]

\[
\frac{L_A}{L_B} = 2^4 \quad \Rightarrow \quad L_A = 16 \times L_B
\]

Therefore: star A is 16× brighter than star B
2 stars are the same temperature, \((T_A = T_B)\), but star A is 2\times \textbf{bigger} than star B \((R_A = 2R_B)\):

\[
\frac{L_A}{L_B} = \frac{4\pi R_A^2 \alpha T_A^4}{4\pi R_B^2 \alpha T_B^4} \implies \frac{L_A}{L_B} = \frac{(2R_B)^2}{R_B^2}
\]

\[
\frac{L_A}{L_B} = 2^2 \implies L_A = 4 \times L_B
\]

Therefore: star A is 4\times \textbf{brighter} than star B.
Hertzsprung-Russell Diagram

- Plot of Luminosity versus Temperature:
  - estimate T from Spectral Type
  - estimate L from apparent brightness & distance

- Done independently by:
  - Eljnar Hertzsprung (1911) for star clusters
  - Henry Norris Russell (1913) for nearby stars
Main Sequence

• Most nearby stars (85%), including the Sun, lie along a diagonal band called the

Main Sequence

• Ranges of properties:
  – \( L = 10^{-2} \) to \( 10^6 \) \( L_{\text{sun}} \)
  – \( T = 3000 \) to \( >50,0000 \) K
  – \( R = 0.1 \) to \( 10 \) \( R_{\text{sun}} \)
Giants & Supergiants

• Two bands of stars *brighter* than Main Sequence stars of the *same* Temperature.
  – Means they must be *larger* in radius.

• **Giants**
  \[ R = 10^{-100} R_{\text{sun}} \quad L = 10^3 - 10^5 L_{\text{sun}} \quad T < 5000 \text{ K} \]

• **Supergiants**
  \[ R > 10^3 R_{\text{sun}} \quad L = 10^5 - 10^6 L_{\text{sun}} \quad T = 3000 - 50,000 \text{ K} \]
White Dwarfs

- Stars on the lower left of the H-R Diagram *fainter* than Main Sequence stars of the *same* Temperature.
  - Means they must be *smaller* in radius.
  - L-R-T Relation predicts:
    \[ R \sim 0.01 \, R_{\text{sun}} \] (~ size of Earth!)
Hipparcos

H-R Diagram

4902 single stars with distance errors of <5%
Luminosity Classification

• Absorption lines are **Pressure-sensitive**:  
  – Lines get **broader** as the pressure **increases**.  
  – Larger stars are puffier, which means lower pressure, so that  
  **Larger Stars** have **Narrower Lines**.

• This gives us a way to assign a **Luminosity Class** to stars based solely on their spectra!
Luminosity Effects in Spectra

Hydrogen Balmer lines:

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350 400 450 500

Wavelength (nm)

K line of ionized calcium

Supergiant
Giant
Main Sequence
Luminosity Classes:

Ia = Bright Supergiants
Ib = Supergiants
II = Bright Giants
III = Giants
IV = Subgiants
V = Dwarfs = Main-Sequence Stars
Spectral + Luminosity Classification of Stars:

- **Sun:**
  G2v (G2 Main-Sequence star)
- **Winter Sky:**
  Betelgeuse: M2 Ib (M2 Supergiant star)
  Rigel: B8 Ia (B8 Bright Supergiant star)
  Sirius: A1v (A1 Main-Sequence star)
  Aldebaran: K5 III (K5 Giant star)
Any theory of stellar structure must explain the observed properties of stars.

Seek clues in correlations among the observed properties, in particular:
- Mass
- Luminosity
- Radius
- Temperature
H-R Diagram

- Temperature (K)
- Luminosity ($L_{\odot}$)

Supergiants, Giants, Main Sequence, White Dwarfs
• **Main Sequence:**
  - Strong correlation between Luminosity and Temperature.
  - Holds for 85% of nearby stars including the sun

• **All other stars differ in size:**
  - Giants & Supergiants:
    Very large radius, but same masses as M-S stars
  - White Dwarfs:
    Very compact stars: \( \sim R_{\text{earth}} \) but with \( \sim M_{\text{sun}} \)!
Mass ($M_{\odot}$) vs. Luminosity ($L_{\odot}$)

$L \propto M^{3.5}$
Mass-Luminosity Relationship

• For Main-Sequence stars:

\[ \left( \frac{L}{L_{\text{sun}}} \right) = \left( \frac{M}{M_{\text{sun}}} \right)^{3.5} \]

In words:

“More massive M-S stars are more luminous.”

Not true of Giants, Supergiants, or White Dwarfs.
$L \propto M^{3.5}$
Stellar Density

• **Density** = Mass ÷ Volume

• **Main Sequence**: small range of density
  – Sun: \( \sim 1.6 \ \text{g/cc} \)
  – O5v Star: \( \sim 0.005 \ \text{g/cc} \)
  – M0v Star: \( \sim 5 \ \text{g/cc} \)

• **Giants**: \( 10^{-7} \ \text{g/cc} \)

• **White Dwarfs**: \( 10^5 \ \text{g/cc} \)
Interpreting the Observations:

- **Main-Sequence Stars:**
  - Strong L-T Relationship on H-R Diagram
  - Strong M-L Relationship
  Implies they have similar internal structures & governing laws.

- **Giants & White Dwarfs:**
  - Must have very different internal structures than Main-Sequence stars of similar mass.
Summary

• Color of a star depends on its Temperature
  – Red Stars are Cooler
  – Blue Stars are Hotter

• Spectral Classification
  – Classify stars by their spectral lines
  – Spectral differences mostly due to Temperature

• Spectral Sequence (Temperature Sequence)
  • O B A F G K M L T
Summary:

- The Hertzsprung-Russell (H-R) Diagram
  - Plot of Luminosity vs. Temperature for stars.
- Features:
  - Main Sequence (most stars)
  - Giant & Supergiant Branches
  - White Dwarfs
- Luminosity Classification
- Mass-Luminosity Relationship
Summary:

- Observational Clues to Stellar Structure:
  - H-R Diagram
  - Mass-Luminosity Relationship
  - The Main Sequence is a sequence of Mass
Questions

• What does the temperature of a star mean?
• Are there stars with temperatures higher than 50000K?
• Are hotter stars brighter than cooler stars? Are they more luminous?
• Why did it take so long to find L & T stars?
Questions:

- Why don’t stars have just any Luminosity and Temperature?
- Why is there a distinct Main Sequence?

**Answer:**
Patterns on the H-R Diagram are telling us about the internal physics of stars.